Journal of Forestry Research (2014) 25(3): 671−676
DOI 10.1007/s11676-014-0506-6

ORIGINAL PAPER

# Propagation behavior of acoustic wave in wood

Huadong Xu • Guoqi Xu • Lihai Wang • Lei Yu

Received: 2013-09-23; Accepted: 2013-10-29


**Abstract:** We used acoustic tests on a quarter-sawn poplar timbers to study the effects of wood anisotropy and cavity defects on acoustic wave velocity and travel path, and we investigated acoustic wave propagation behavior in wood. The timber specimens were first tested in unmodified condition and then tested after introduction of cavity defects of varying sizes to quantify the transmitting time of acoustic waves in laboratory conditions. Two-dimensional acoustic wave contour maps on the radial section of specimens were then simulated and analyzed based on the experimental data. We tested the relationship between wood grain and acoustic wave velocity as waves passed in various directions through wood. Wood anisotropy has significant effects on both velocity and travel path of acoustic waves, and the velocity of waves passing longitudinally through timbers exceeded the radial velocity. Moreover, cavity defects altered acoustic wave time contours on radial sections of timbers. Acoustic wave transits from an excitation point to the region behind a cavity in defective wood more slowly than in intact wood.

**Keywords:** acoustic wave, propagation behavior, wood, velocity

## Introduction

Acoustic technologies for testing wood products have been introduced to the field of forestry and the wood industry for a few decades. Compared with other testing techniques such as nuclear magnetic resonance (Hernández and Cáceres 2010), X-rays (Yu and Qi 2008), and vibration, acoustic wave tests have the advantages of low cost, portability, safety for testing personnel, and rapid return of results. These features increase the suitability of acoustic wave testing for in situ tests of wood engineering materials and field measurement of standing trees. Two dimensional acoustic wave tomography broadens the scope for application of acoustic wave testing. Acoustic wave testing has become one of the most popular and effective nondestructive wood testing methods, and it is widely used to assess the physical and mechanical qualities of wood (Sandoz 1989; Halabe et al. 1997), detect internal defects in logs or standing trees (Bucur 2005; Ross et al. 1994), evaluate the strength and residual life of the major components of timber structures (Yang et al. 2012), determine the stability of roadside trees in cities (Mattheck and Bethge 1993; Wang 1999) and analyze the vibration properties of musical instruments manufactured of wood (Brémaud 2012).

In tests using acoustic waves, one acoustic parameter, such as acoustic wave velocity (AWV), is generally employed. For example, to detect internal defects in standing trees, AWV is compared between healthy trees and defective trees and then used to evaluate the locations and sizes of defects such as knots, fungal decay, or cracks based on changes AWV magnitude (Divos and Szalai 2002). In assessments of the mechanical quality of standing trees or structural beams, the dynamic properties of wood such modulus of elasticity (MOE) are quantified using AWV, and then the static properties of wood are evaluated based on the linear relationship between the dynamic and static properties (Brashaw et al. 2004).

The basis of these applications is understanding of the fundamentals of acoustic wave propagation in wood, especially their propagation behavior in intact wood. Few studies have focused on the propagation path of acoustic waves in intact wood or the effects on propagation paths of defects such as knots and decay. The objective of this study was to examine the propagation path of acoustic waves in intact and defective wood (with cavity defects) to enhance understanding of wave propagation behavior. We analyzed the effects of wood anisotropy and cavity defects on acoustic wave propagation paths.

## Materials and methods

### Wood samples

Wood samples were quarter-sawn Ussuri poplar (*Populus us-*

Project funding: This work was financially supported by "the national natural science foundation of China (31300474)", "China Postdoctoral Science Foundation funded project (2014M551203)" and "the Fundamental Research Funds for the Central Universities of China (DL12BB18), (DL11CB02) and (2572014CB35)".



Huadong Xu, Guoqi Xu, Lihai Wang (✉), Lei Yu
Northeast Forestry University, Harbin, China 150040.
E-mail: lihaiwang@yahoo.com

Corresponding editor: Yu Lei

*suriensis*) timbers measuring 76 cm long, 7 cm thick, and 34–35 cm wide (Fig. 1). The moisture content of heartwood and sapwood of the timbers were 83.3% and 99.5%, respectively.

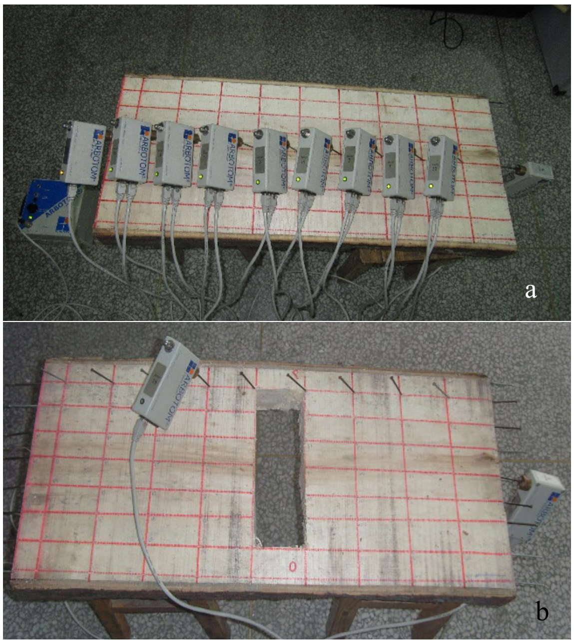


**Fig.1:** Specimen and instruments for measuring the acoustic wave time

Arranging measuring points

To study the propagation process and behavior of acoustic wave in radial sections of lumber, a series of grids was drawn on the radial section to be used to measure the transmission time of acoustic waves point by point. Fig. 2 depicts nine measuring points along the radial direction of specimen at 4 cm intervals, and nine measuring points along the longitudinal direction at 8 cm intervals. The distance between the last two columns points was 4 cm, for example the distance from Point 82 to Point 99. Additionally, six measuring points were drawn between Point 1 and Point 18. Thus, there were one hundred and six measuring points on the radial section of the sample lumber. The locations and areas of cavities are shown in Fig. 1(b) and Table 1.

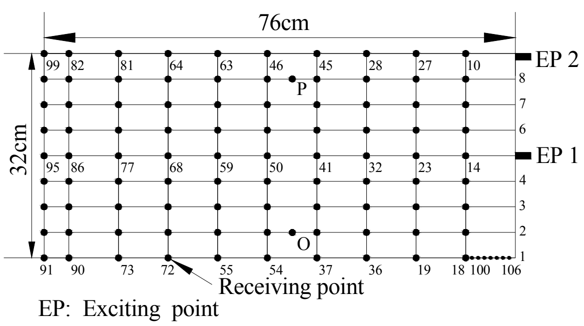


**Fig. 2:** Arrangement of measuring points

**Table 1:** The location and area of the rectangular cavity artificially drilled in wood specimen

| | Four corner points | Area ($cm^2$) | Ratio of cavity area to lumber radial section area (%) |
|---|---|---|---|
| Cavity 1 | 38, 44, P, O | 96 | 3.95 |
| Cavity 2 | 38, 44, 47, 53 | 192 | 7.90 |
| Cavity 3 | 29, 35, 47, 53 | 384 | 15.79 |
| Cavity 4 | 29, 35, 36, 62 | 576 | 23.68 |

Instruments and methods

*Rate of wave transmission in longitudinal and radial directions*

We used the Arbotom instrument, produced by RINNTECH Company with an exciting sensor and a series of nreceiving sensors, to measure acoustic wave transmission times (AWTs) (Fig. 1). When measuring each point, we used a hammer to knock on the exciting sensor 5−10 times with the same intensity of force, and then calculated the average values of AWT.

To discuss the differences in acoustic wave propagation between heartwood and sapwood, AWV was tested in the longitudinal direction once at 2 cm interval along the short edge of specimen using an acoustic wave timer. The tests were conducted nine times on heartwood, seven times on sapwood, and twice on bark. In total, we recorded 18 data sets for longitudinal transmission times of acoustic waves. Transmission times were then tested for radial acoustic waves between points 1 and 9, points 46 and 54, and points 91 and 99.

*Measuring AWT by grid point method*

Measurement by grid points included two parts: (1) Point 5 served as Exciting Point 1 (EP1) and the receiving points were from Point 10 to Point 99 in sequence; (2) Point 9 served as Exciting Point 2 (EP2), and the receiving points were from Point 10 to Point 106 in sequence (Fig. 2). After measuring AWT, the transmission time isolines were drawn on the radial section of lumber specimens with Matlab software.

By measuring the distance between the exciting point and each receiving point, we computed the angle between the propagation direction of the acoustic wave and wood fiber direction. At the same time, AWV was calculated using function (1), which was used to analyze the relationship between wave propagation velocity and propagation direction.

$$V = \frac{L}{T} \tag{1}$$

Where, $V$ is acoustic wave velocity ($m \cdot s^{-1}$), $L$ is propagation distance (m), $T$ is acoustic wave transmission time (s).

## Results and discussion

Comparison between longitudinal and radial AWV

AWV moved more quickly in heartwood than in sapwood, and moved slowest in bark (Table 2). The propagation directions of

acoustic waves both in heartwood and in sapwood were along the grain direction (parallel to the wood fiber direction), so the reason for this difference may be due to the varying moisture content of wood. The moisture content of sapwood was higher than that of heartwood in sample timbers. Moisture content can affect the propagation of acoustic waves and AWV typically declines as wood moisture content increases (Sandoz 1989).

The comparison of propagation velocity between longitudinal and radial acoustic waves in lumber specimens is shown in Fig. 3. AWV was greater in the longitudinal direction than that in radial direction (Fig. 3); mean radial AWV was 508 $m \cdot s^{-1}$. The main reason for this might have been the anisotropy of wood. The propagation direction of the longitudinal acoustic wave was parallel to the direction of wood fibers and the propagation direction of radial acoustic waves was perpendicular to the direction of wood fibers. Wood grain direction had a significant effect on the propagation of acoustic waves.

**Table 2:** Propagation velocity of longitudinal acoustic waves in lumber specimen

| Category | Propagation velocity of longitudinal acoustic waves | | | | |
|---|---|---|---|---|---|
| | No. | Mean ($m \cdot s^{-1}$) | Max. ($m \cdot s^{-1}$) | Min. ($m \cdot s^{-1}$) | Standard deviation ($m \cdot s^{-1}$) |
| Heart wood | 9 | 3900 | 4109 | 3695 | 188.30 |
| Sapwood | 7 | 3381 | 3598 | 3210 | 140.01 |
| Bark | 2 | 2316 | 2350 | 2282 | 48.08 |

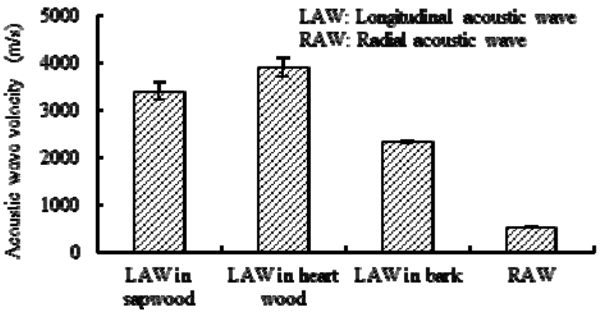


**Fig. 3:** Comparison of propagation velocity between longitudinal and radial acoustic waves

Transmitting time isolines of acoustic wave in intact wood

The transmission times for acoustic waves received at each receiving point in the radial section of lumber specimen when Exciting Point 1 and Exciting Point 2 are knocked on respectively, were processed using Matlab to simulate the transmission time isolines of acoustic waves (Fig. 4).

The acoustic wave is gradually transmitted from the wood pith to the far area in the radial section of lumber when EP 1 is knocked on (Fig. 4a). AWV varied by direction, with longitudinal travel most rapid and radial travel most slow. In the transition area from longitudinal to radial, the transmission time changed gradually from long to short. In other words, there were more isolines per unit length in the radial than in the longitudinal direction. Acoustic wave transmits gradually from near to far in the radial section of lumber when EP2 was knocked on (Fig. 4b). Acoustic waves travelled most rapidly and there were fewer isolines when waves travelled in the longitudinal direction. Waves travelled most slowly and there are more isolines in the radial direction.

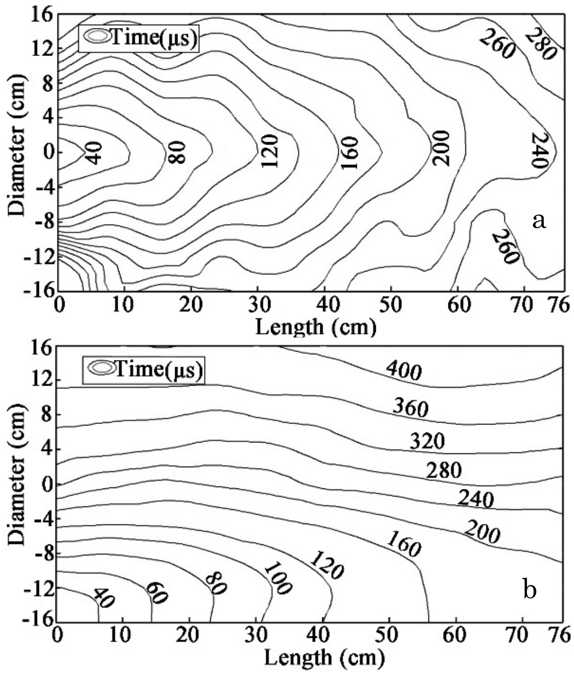


**Fig. 4:** Transmitting time isolines of acoustic wave in radial section of log when EP1 and EP2 are knocked on

Relationship between wood grain and AWV

The definition of grain angle ($\theta$) between acoustic wave propagation direction and wood fiber direction is shown in Fig. 5.

The relationship scatter diagram between $\theta$ and AWV in different directions is shown in Fig. 6. AWV was highest at $\theta = 0°$ and lowest at $\theta = 90°$. AWV decreased gradually as $\theta$ increased. AWV decreased quickly at $\theta < 45°$ but decreased more slowly at $\theta \geq 45°$.

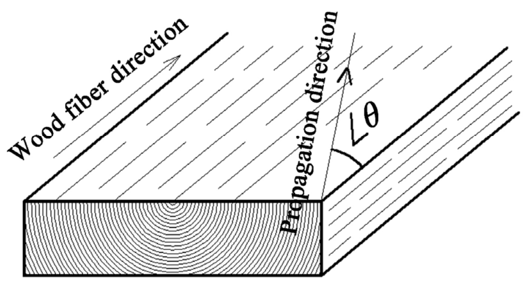


**Fig. 5:** The illustration diagram of the grain angel

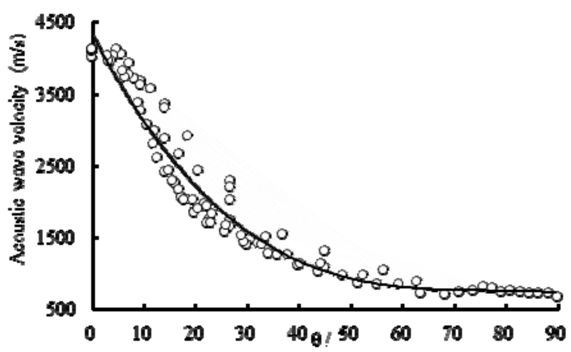


**Fig. 6:** Effect of grain angel on the propagation velocity of acoustic wave

Prediction models of AWV

Kabir et al. (2001) used the second order parabolic function (Equ. 2) to study the relationship between AWV and grain angle, and concluded that the resulting model could be used to predict AWV in veneer. We also used the model to discuss the relationship between $\theta$ and AWV.

$$V_\theta = A + B\theta + C\theta^2 \tag{2}$$

Where, $V_\theta$ is AWV at $\theta$, and $A$, $B$, and $C$ are regression coefficients.

The regression equation for the relationship between $\theta$ and AWV traveling in a radial section of lumber is:

$$V_\theta = 4189.1 - 110.59\theta + 0.8459\theta^2 \quad R^2 = 0.95 \tag{3}$$

For studying the relationship between wave velocity and wood mechanical properties, the most classical empirical formula is the Hankinson formula designed by the U.S. Army in 1921. Eq. 4 is one of its forms, which can be used to predict AWV (Armstrong et al. 1991).

$$V_\theta = \frac{V_0 V_{90}}{V_0 \sin^n \theta + V_{90} \cos^n \theta} \tag{4}$$

Where, $V_\theta$ is AWV at $\theta$; $V_\theta$ is AWV parallel to the wood fiber direction; $V_{90}$ is AWV perpendicular to the wood fiber direction; $n$ is an empirical constant ranging from 1.5–2.5.

Predicted AWVs using Hankinson formula and the parabolic function are shown in Fig. 7. In the Hankinson formula, $V_0$ and $V_{90}$ were 4095 m·s$^{-1}$ and 680 m·s$^{-1}$, respectively, and $n$ was 1.7. Both of these models described the relationship between propagation directions and AWV, but the predicted data using the Hankinson formula yielded greater agreement with the experimental data.

Effect of cavity defects on AWT isolines

AWT isolines were drawn on the radial sections of defective wood when EP1 was excited (Fig. 8a). Compared with Fig. 4a, Fig. 8a shows that AWT isolines on the radial section of defective wood differed significantly from those on intact wood. When wood specimens contained cavities, acoustic wave time isolines behind the rectangular cavities formed two "circular regions". AWT from EP1 to these two regions was greater than to other region of wood in radial sections. AWT in defective wood was twice that from EP1 to these two regions in intact wood. AWTs from EP1 to other regions behind the rectangular cavity except those two regions were greater than in intact specimens. Similarly, compared with Fig. 4b, Fig.8b shows that AWTs from EP2 to the area behind the cavity in defective wood were larger than in intact wood. AWT isolines from EP2 in defective wood also formed "circular regions" near the farthest corner of the rectangular cavity.

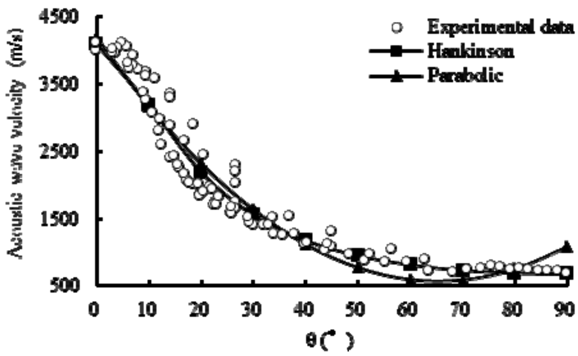


**Fig. 7:** Experimental and predicted acoustic wave velocity using different equations

## Conclusion

When an acoustic wave transmits across a radial section of lumber, the propagation velocity in the longitudinal direction (parallel to the wood fiber) was higher than in the radial direction (perpendicular to the wood fiber).

Acoustic waves were gradually transmitted from excitation points to other areas in the radial section of lumber. There were more transmitting time isolines per unit length in radial directions than in longitudinal directions.

Acoustic wave velocity declined gradually with increasing $\theta$. It decreased quickly at $\theta$ <45°, and decreased slowly at θ >45°. The predicted velocities using the second order parabolic model and Hankinson's formula were in close agreement with the measured values. Compared with the parabolic model, Hankinson's formula predicted more accurately at $n$ >1.7.

Acoustic wave time isolines on radial sections of defective wood differed from those on intact wood. Acoustic wave transmission time from the exciting point to the region behind the cavity was larger in defective wood than in intact wood.

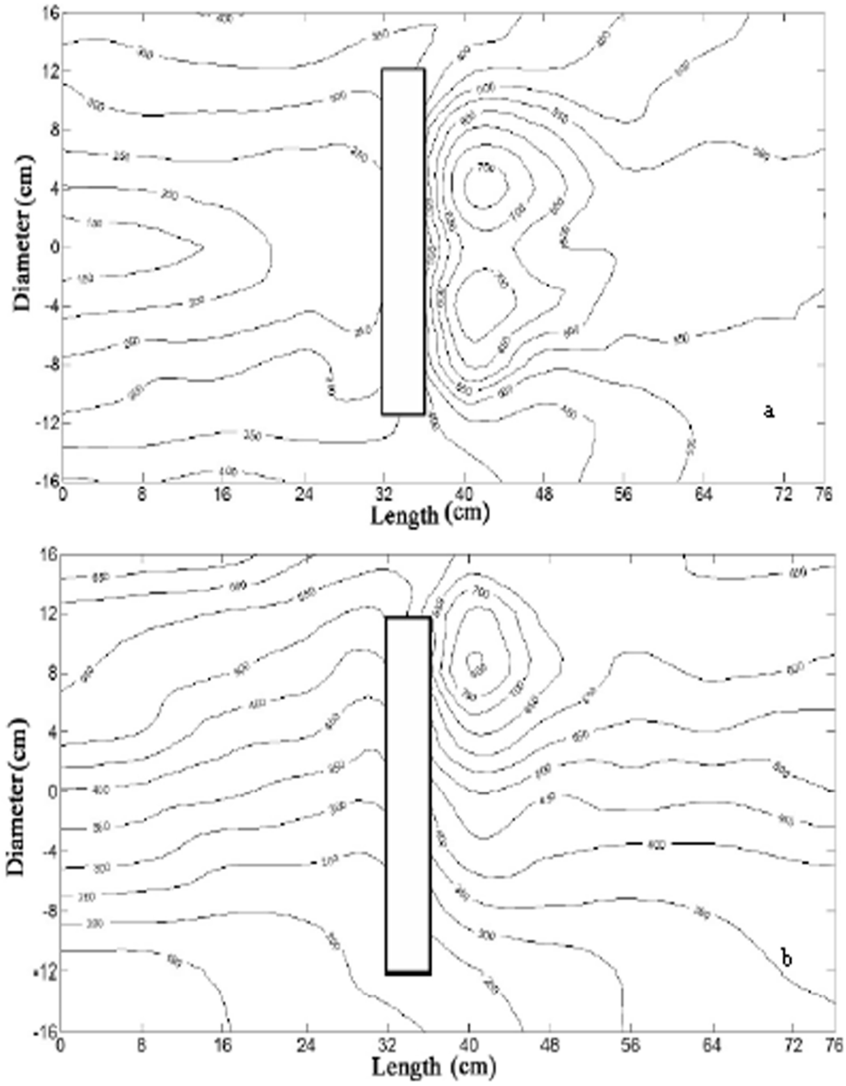


**Fig. 8:** Effect of cavity defect on acoustic wave time isolines on the radial section of green wood. (a) and (b) are the acoustic wave time isolines on the wood with Cavity 1 when EP1 and EP2 are excited, respectively.

## References


Armstrong JP, Patterson DW, Sneckenberger JE. 1991. Comparison of three equations for predicting stress wave velocity as a function of grain angle. *Wood and Fiber Science*, **23**(1): 32–43.

Brémaud I. 2012. Acoustical properties of wood in string instruments soundboards and tuned idiophones: Biological and cultural diversity. *Journal of the Acoustical Society of America*, **131**(1): 807−818.

Brashaw BK, Wang XP, Ross RJ, Pellerin RF. 2004. Relationship between stress wave velocities of green and dry veneer. *Forest Products Journal*, **54**(6): 85−89.

Bucur V. 2005. Ultrasonic techniques for nondestructive testing of standing trees. *Ultrasonics*, **43**(4): 237−239.

Divos F, Szalai L. 2002. Tree evaluation by acoustic tomography. *In*: *Proceedings of the 13th International Symposium on Nondestructive Testing of Wood*, pp. 251−256.

Halabe UB, Bidigalu GM, GangaRao HV, Ross RJ. 1997. Nondestructive Evaluation of Green Wood Using Stress Wave and Transverse Vibration Techniques. *Materials Evaluation*, **55**(9): 1013−1018.

Hernández RE, Cáceres CB. 2010. Magnetic resonance microimaging of liquid water distribution in sugar maple wood below fiber saturation point. *Wood and Fiber Science*, **42**(3): 259−272.

Kabir MF. 2001. Prediction of ultrasonic properties from grain angle. *Journal of the Institute of Wood Science*, **15**(5): 235−246.

Mattheck CG, Bethge KA. 1993. Detection of decay in trees with the Metriguard Stress Wave Timer. *Journal of Abroriculture*, **19**(6): 374−378.

Ross RJ, Ward JC, TenWolde A. 1994. Stress wave nondestructive evaluation of wetwood. *Forest Products Journal*, **44**(7/8): 79−83.

Sandoz JL. 1989. Grading of construction timber by ultrasound. *Wood Sci-*

*ence and Technology*, **23**: 95–108.

Wang LH, Xu HD, Zhou CL, Li L, Yang XC. 2007. Effect of sensor quantity on measurement accuracy of log inner defects by using stress wave. *Journal of Forestry Research*, **18**(3): 221–225.

Wang XP. **1999**. Stress wave-based nondestructive evaluation (NDE) methods for wood quality of standing trees. Doctoral Dissertation. Houghton: Michigan Technological University.

Yang HS, Kang J, Choi MS. 2012. Acoustic effects of green roof systems on a low-profiled structure at street level. *Building and Environment*, **50**: 44–55.

Yu L, Qi DW. **2008**. Analysis and processing of decayed log CT image based on multifractal theory. *Computers and Electronics in Agriculture*, **63**(2): 147–154.

Zhao Y, Zhao N, Fa L, Zhao MS. 2013. Seismic signal and data analysis of rock media with vertical anisotropy. *Journal of Modern Physics*, **4**(1): 11–18.